Welcome to the digital edition of the March/April 2021 issue of CERN Courier.

Hadron colliders have contributed to a golden era of discovery in high-energy physics, hosting experiments that have enabled physicists to unearth the cornerstones of the Standard Model. This success story began 50 years ago with CERN’s Intersecting Storage Rings (featured on the cover of this issue) and culminated in the Large Hadron Collider (p38) – which has spawned thousands of papers in its first 10 years of operations alone (p47). It also bodes well for a potential future circular collider at CERN operating at a centre-of-mass energy of at least 100 TeV, a feasibility study for which is now in full swing.

Even hadron colliders have their limits, however. To explore possible new physics at the highest energy scales, physicists are mounting a series of experiments to search for very weakly interacting “slim” particles that arise from extensions in the Standard Model (p25).

Also celebrating a golden anniversary this year is the Institute for Nuclear Research in Moscow (p33), while, elsewhere in this issue: quantum sensors target gravitational waves (p10); X-rays go behind the scenes of supernova 1987A (p12); a high-performance computing collaboration forms to handle the big-physics data onslaught (p22); Steven Weinberg talks about his latest work (p51); and much more.

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It’s ALL about the DETAILS
The rewards of bold thinking

B

ek in the early 1960s, as this month’s cover feature on detectors (p34), discussion raged at CERN about the next best step for particle physics. At the time, the high-energy frontier was commanded by the great proton synchrotron, such as Brookhaven’s Cosmotron and, later, CERN’s Proton Synchrotron, which drove fixed-target experiments. But a new type of machine capable of exploiting the full energy of proton beams for the production of new particles – the hadron collider – was reviving up in the sidelines. In December 1965, the CERN Council approved the construction of the Intersecting Storage Rings (ISR) over a very high-energy proton synchrotron, although the latter would materialise 10 years later in the Super Proton Synchrotron (SPS). The ISR’s first proton-proton collisions, which reached a centre-of-mass energy of 38 GeV, took place on 27 January 1971, opening the era of hadron colliders.

From the ISR came the ingenious conversion of the SPS into a proton-antiproton collider (SppS), the demonstration of large-scale superconducting magnet technology for the Tevatron at Fermilab, and the LHC, whose elegant magnet design has enabled the highest collision energies (13 TeV) and luminosities to date. Each machine, and its increasingly complex detectors, was a step into the unknown, requiring the invention of new technologies and sharp political and organisational skills to build and operate ever larger facilities. The payoff was the discovery of the Standard Model’s most ambitious long-term technological path in undertaking a feasibility study for a future circular hadron collider with a centre-of-mass energy of at least 100 TeV. If built, the success of this mother of all hadron colliders will have each generation of previous machine and its detectors to thank.

Know your limits

As productive as hadron colliders are in probing nature at the highest energies, many current mysteries, such as dark matter and the origin of neutrino masses, may well originate from phenomena at energy scales inaccessible to any collider imaginable. Fortunately, models involving such scales can be tested now and in the near future by a series of experiments – some using magnets from the LHC and HERA in fact - searching for very weakly interacting “slim” particles that arise in extensions of the Standard Model (see p25). Effective field theory is another powerful tool to pursue such signals from far beyond the TeV scale, explains Steven Weinberg in this issue’s interview (p55).

European strategy for particle physics, CERN is exploring the most ambitious long-term technological path in undertaking a feasibility study for a future circular hadron collider with a centre-of-mass energy of at least 100 TeV. If built, the success of this mother of all hadron colliders will have each generation of previous machine and its detectors to thank.
### News Analysis

#### Antimatter

**AEGIS on track to test free fall of antimatter**

The AEGIS collaboration at CERN’s Antiproton Decelerator (AD) has reported a milestone in its bid to measure the gravitational free fall of antimatter – a fundamental test of the weak equivalence principle. Using a series of techniques developed in 2018, the team demonstrated the first pulsed production of antiautos, which allows the time at which the antiautos are formed to be known with high accuracy. This is a key step in determining “g” for antimatter.

“This is the first time that pulsed formation of antihydrogen has been established on timescales that open the door to simultaneous manipulation, by lasers or external fields, of the formed atom, as well as to the possibility of applying the same method to the pulsed formation of other antiprotonic atoms,” says AEGIS spokesperson Michael Doser of CERN. “Knowing the moment of antihydrogen formation is a powerful tool.”

General relativity’s weak equivalence principle holds that all particles with the same initial position and velocity should follow the same trajectory in a gravitational field. It has been verified for matter with an accuracy approaching 10⁻²⁵. Since theories beyond the Standard Model such as supersymmetry, or the existence of Lorentz-symmetry violating terms, do not necessarily lead to an equivalent force on matter and antimatter, finding the slightest difference in g could reveal the presence of quantum effects in the gravitational arena. Indirect arguments constrain possible differences to below 10⁻²⁷ g, but no direct measurement for antimatter has yet been performed due to the difficulty in producing and containing large quantities of it.

Antihydrogen’s neutrality and long lifetime make it an ideal system in which the formation of antihydrogen atoms can be established with high accuracy. The moment of production of antihydrogen is critical for determining the gravitational free fall of antimatter. AEGIS has employed an alternative charge–exchange process between trapped and cooled antiprotons and positronium (a 3⁺ bound system) to produce antihydrogen atoms. The moments of production are associated with the firing time and the transit time of positrons, enabling precise determination of the time at which antihydrogen is produced.

**Further reading**

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JINR
NICA booster achieves first beam
After seven years of construction at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, the Booster synchrotron at the brand-new NICA (Nuclotron-Based Ion Collider Facility) Complex has accelerated its first beam. On 19 December helium ions were injected into the synchrotron and a stable circulation of the beam was obtained at an energy of 3.2 MeV, a milestone towards NICA’s scheduled completion in 2022.

NICA will allow studies of the properties of nuclear matter in the region of maximum baryonic density. By colliding heavy gold ions at energies corresponding to the deconfinement phase transition (a GATI), NICA will access the transition of the quark–gluon plasma into hadrons, complementing studies at higher energy colliders such as the LHC.

The NICA booster is a 213 m circumference superconducting synchrotron that will accelerate beams to 500 MeV into 503 m storage rings, which will collide the beams at two detectors: the Multi-Purpose Detector, designed to study dense baryonic matter; and the Spin-Physics Detector, designed to study collisions between polarised beams of protons and deuterons.

The complex is one of six Russian “megascience” facilities that are part of the CREMLIN project, which aims to use large-scale science to improve human health, environment and climate, and strengthen relations and networks between European and Russian research infrastructures. The CREMLIN consortium comprises European and Russian research infrastructures, including CERN and DESY. Other proposed “megascience” facilities included in this project are the Super-Charm-Tau Factory at the Budker Institute of Nuclear Physics, and the Special-purpose Synchrotron-Radiation Source (SIBS-4) at the NRC Kurchatov Institute.

“This is a historic moment for our laboratory and a great milestone in the realisation of our flagship megascience project – we have to thank the CREMLIN grant programme for helping us in these challenges,” says Vladimir Kekelidze, the NICA project leader.

Positive feedback
Global iodine emissions at high latitudes have increased threefold during the past seven decades and are likely to continue to increase in the future as sea ice becomes thinner. Iodine aerosol production could accelerate Arctic melting.
Quantum technologies

Quantum sensing for particle physics

A particle physics-led experiment called AION (Atomic Interferometric Observatory and Network) is one of several multidisciplinary projects selected for funding by the UK’s new Quantum Technologies for Fundamental Physics programme. The successful projects, announced in January following a £3 million call for proposals from UK Research and Innovation (UKRI), will explore recent advances in quantum technologies to tackle outstanding questions in fundamental physics, astrophysics and cosmology.

UKRI and university funding of about £40 million (UKRI part £27.5 million) will enable the AION team to prepare the construction of a 10-m± atomic interferometer at the University of Oxford to explore ultra-light dark matter and provide a pathway towards detecting gravitational waves in the unexplored mid-frequency band ranging from several mHz to a few Hz. The setup will use lasers to drive transitions between the ground and excited states of a cloud of cold strontium atoms in free fall, effectively acting as beam splitters and mirrors for the atomic de Broglie waves (see figure). Ultra-light dark matter and exotic light bosons would be expected to have differential effects on the atomic transition frequencies, while a passing gravitational wave would generate a strain in the vacuum state, the development of ultra-low-noise quantum electronics to underpin searches for a bosons and light hidden particles; quantum simulators to mimic the extreme conditions of the early universe and black holes; and the development of quantum-enhanced superfluid technologies for cosmology.

The UKRI call is part of a global effort to develop quantum technologies that could bring about a “second quantum revolution”. Several major international public and private initiatives are under way. Last autumn, CERN launched its own quantum technologies initiative (CERN Courier, September/October 2020, p27), “With the application of emerging quantum technologies, I believe we have an opportunity to change the way we search for answers to some of the biggest mysteries of the universe,” said Mark Thomson, executive chair of the UK’s Science and Technology Facilities Council. “These include exploring what dark matter is made of, finding the absolute mass of neutrinos and establishing how quantum mechanics fits with gravity.”

Neutrinos

Farewell Daya Bay, hello JUNO

In October 2007, neutrino physicists broke ground 54km north-east of Hong Kong, to build the Daya Bay nuclear reactor experiment. Comprising eight 20-tonne liquid-scintillator detectors situated within 1km of the Daya Bay nuclear plant, its aim was to look for the disappearance of electron antineutrinos as a function of distance to the reactor. This would constitute evidence for mixing between the electron and the third neutrino mass eigenstate, as described by the parameter $\theta_{13}$. Back then, $\theta_{13}$ was the least well-known angle in the neutrino sector and had no upper limit available. Today, it is the best known angle by some margin, and the knowledge that it is nonzero has opened the door to measuring light neutrino masses and establishing the neutrino mass hierarchy.

Daya Bay was one of a trio of experiments located in close proximity to nuclear reactors, along with RENO in South Korea and DoubleChooz in France, which were responsible for this seminal measurement. DoubleChooz published the first hint that $\theta_{13}$ was nonzero in 2010, before Daya Bay and RENO established this conclusively the following spring. The experiments also failed to dispel the reactor–antineutrino anomaly, whereby observed neutrino fluxes are a few percent lower than calculation predict. This has triggered a slew of new experiments looking for anomalies in nuclear reactor cores, in search of evidence for oscillations involving additional, sterile light neutrinos. As the Daya Bay experiment’s detectors are dismantled, after almost a decade of data taking, the three collaborations can reflect on the rare privilege of having panned the value of previously unknown parameters into the Standard – Model Lagrangian.

Funding Daya Bay co-spokesperson Yi-Fang Wang says the experiment has a transformative effect on particle physics, emboldening the country to take on major projects such as a circular electron–positron collider. “One important lesson we learnt from Daya Bay is that we should just go ahead and do it if it is a good project, rather than waiting until everything is ready. We convinced our government that we could do a good job, that world-class jobs need not be international, and particle physics is fundamental and influential, and deserves to be supported.”

The experiment has also paved the way for China to build a successor, the Jiangmen Underground Neutrino Observatory (JUNO), for which Wang is now spokesperson. JUNO will aim to establish the neutrino mass hierarchy – the question of whether the third neutrino mass eigenstate is the most or least massive of the three. An evolution of Daya Bay, the new experiment will also measure a deficit of electron antineutrinos, but at a distance of 53km, seeking to resolve fast and shallow oscillations that are expected to differ depending on the neutrino mass hierarchy (CERN Courier, July/August 2020, p12).

In the early 2020s the JUNO facility will be underground at the Daya Bay site, but it will have a much larger detector. “We convinced our government that we should just go ahead and do it if it is a good project, rather than waiting until everything is ready,” Wang said. “We convinced our government that we could do a good job, that world-class jobs need not be international, and particle physics is fundamental and influential, and deserves to be supported.” The detector concept that the three experiments used to uncover $\theta_{13}$ was designed by the Double Chooz collaboration. Thierry Lasserre, one of the experiment’s two founders, recalls that it was difficult, 20 years ago, to convince the community that the measurement was possible at reactors. “It should not be forgotten that significant experimental efforts were also undertaken in Angra dos Reis, Braidwood, Diablo Canyon, Krasnoyarsk and Kashiwazaki,” he said. “If we had that capability, we could have explored the possibility of using that capability.”

TransformativeAntineutrino detection is submerged in underground water of one of Daya Bay’s experimental sites.

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Lifting the veil on supernova 1987A

On 23 February 1987 astronomers around the world saw an extremely bright supernova, now called SN1987A. It was the closest supernova observed for over 300 years and was visible to the naked eye. The event was quickly confirmed to be the result of the collapse of “Sanduleak –69 202”, a blue supergiant star in the Large Magellanic Cloud. As the first nearby supernova in the era of modern astronomy, SN1987A remains one of the most monitored objects in the sky. Apart from confirming several important theories, such as radioactive decay being the source of the observed optical emission, the supernova also raised a number of questions that remain unanswered. The most important is: where is the remnant of the progenitor star?

Despite several false detection claims in the past, evidence is mounting that Sanduleak –69 202 collapsed into a neutron star that is becoming more visible as the dust around it starts to settle.

A new analysis by researchers in Italy and Japan based on high-energy X-ray data from the Chandra and NuSTAR space telescopes adds the latest support to this idea. Even before the optical light from SN1987A was detected, several neutrino detectors around the world saw a burst of neutrinos. The brightest one was observed by Japan’s Kamiokande II detector, which detected a total of 12 antineutrinos approximately three hours before the first optical light reached Earth. The detection of antineutrinos seemed to confirm theoretical predictions for a star that size of Sanduleak –69 202: namely that it should collapse into a neutron star, and emit large numbers of neutrinos while doing so. The optical light arrives later because it is only produced when the shock waves from the collapse reach the surface of the star. Since the newly formed neutron star would be expected to emit large amounts of energy at various wavelengths, one might assume it would be relatively easy to detect. However, no signals were found in follow-up searches over the past three decades, leading to much speculation about the fate of this star and its surrounding medium.

The first signs of the stellar remnant of SN1987A came from radio observations by the Atacama Large Millimeter/sub-millimeter Array (ALMA) in Chile in 2019. A group led by Phil Cigan from Cardiff University in the UK used ALMA data at various frequencies to study the core of SN1987A. Close to the centre, they found a bright “blob” structure, the emission from which appeared to be compatible with radio emission from particles accelerated by a neutron star, also called a pulsar wind nebula. Although the researchers could not exclude local heating from “Ti” produced during the supernova as the source, the results provided the first hint that the blob houses a young neutron star.

Wind power

Inspired by the ALMA results, Emanuele Greco from the University of Palermo and coworkers started to study the same region using X-ray data from Chandra and NuSTAR taken during 2012, 2013 and 2014. They found that the detected soft X-ray emission (0.5–8keV) was compatible with thermal emission produced in the remnant shock waves of the supernova event with the circumstellar medium. However, at higher energies (10–20keV) the emission was clearly non-thermal in nature. Describing their findings in a preprint posted in January, the group studied the two possible sources for such emission: synchrotron emission from a pulsar wind nebula and synchrotron emission produced in shock waves in the region. Whereas models for both ideas fit the spectral data, the pulsar wind nebula is favoured because the shock emission would not be expected to look like this for such a young remnant.

The reason why this neutron star has escaped previous observations in optical or soft X-ray energies is likely absorption by cold dust emitted during the supernova, which appears to still absorb a large part of the synchrotron emission observed in X-rays, especially at lower energies. But the dust is expected to start to heat up during the coming decades, thereby becoming transparent to lower energy emission. Greco and colleagues predict that, if the emission is indeed induced by a neutron star, it will become visible in the soft X-ray regime by 2030 with Chandra.

Although astronomers have just two observational hints that Sanduleak –69 202 did, as it should according to theory, collapse into a neutron star, it appears that after 25 years of searching we will finally understand what happened in SN1987A.

Further reading

Leading to a distortion of the presence of magnetic fields, general relativistic spacetime, classical electrodynamics in 021104). As a result of embedding stars igniting (between atoms forming and the period in the early universe frequency gravitational waves telescopes to detect high- have proposed using radio Camilo Garcia-Cely (DESY) coupling between photons and upper laboratory limit for the magnetic field of the Penning ALPs interacting with the strong noise, could in fact be caused by antiprotons. Faint signals, which might easily be mistaken for matter (neon, magnesium and silicon). and oxygen) and heavy elements the primary-cosmic-ray spectra may shed light on the processes thrown up another surprise that International Space Station have Spectrometer (AMS-02) on the Cosmic rays get weirder synchrotron X-ray source. also home to DESY's PETRA III the facility will be built, is Hamburg, Germany, where the facility will be built, is also home to DESY's PETRA III superconducting X-ray source.

Dark- age detectors Valerie Domke (CESN) and Camilo Garcia-Cely (DESY) have proposed using radio telescopes to detect high-frequency gravitational waves (GWs) from the “dark ages” – the period in the early universe between atoms forming and stars (igniting (Phys. Rev. Lett. 116 041104). As a result of embedding a classical electrodynamics in general relativistic spacetime, it is expected that GWs can be converted into photons in the presence of magnetic fields, leading to a distortion of the cosmic microwave background. Data from the Square Kilometre Array, which may begin construction in South Africa and Australia as early as this year, could allow the detection of GWs with frequencies in the MHz and GHz regime, far beyond the reach of LSST, VIRGO or KAGRA, wrote the pair.

Industrial innovation DESY virtually kicked-off a new “innovation factory” late last year, allowing detailed planning for the building’s infrastructure to begin. The facility will offer laboratories and spaces for start-ups, scientists and established corporations, in the hope of building strong ties between research and industry. Construction is proposed to begin in 2023, with completion aimed for 2025. Science City Bahrenfeld, a new district in Hamburg, Germany, where the facility will be built, is also home to DESY’s PETRA III synchrotron X-ray source.

Cosmic rays get weirder Results from the Alpha Magnetic Spectrometer (AMS-02) on the International Space Station have thrown up another surprise that may shed light on the processes that create and accelerate cosmic rays. Last year, the collaboration reported unexpected differences in the rigidity (momentum

Novel collider concept Peking University physicists may shed light on the merits of a novel electron–muon collider (arXiv:2010.15144). Collisions between different species of lepton could reduce physics backgrounds for studies of charged-lepton flavour violation and Higgs-boson properties, and the asymmetric nature of the collisions could be used to control troublesome backgrounds caused by muon decays inside the accelerator, argue the authors. The proposal proposes to use electron and muon beams initially, and upgrades culminating in a 10-TeV-scale muon–muon collider.

32 is not a magic number A study at CERN’s SOLDEE facility has exposed shortcomings in the best nuclear models, which cannot reconcile recent measurements of neutron–rich nuclei. 32 had been thought to be a “magic” number of neutrons that completes a nuclear shell and results in a slimmer nucleus with a greater binding energy than its neighbours. However, researchers using the Collinear Resonance Ionisation Spectroscopy apparatus found that potassium-32, which has 33 neutrons, was not observably fatter than the supposedly magic potassium-31, which boasts 30 protons and 32 neutrons (Acc. Phys. Lett. 103 041104).
Evidence for the decay of the Higgs boson to a photon and a low-mass electron or muon pair, propagated predominantly by a virtual photon ($\gamma^*$), $H \rightarrow \gamma^* \gamma$, has been obtained at the LHC. In a recent conference note, the ATLAS collaboration reports a 3.2σ excess over background at $H \rightarrow \gamma \gamma$ decay candidates with dilepton mass $m_\ell^2 < 30$ GeV.

The measurement of rare decays of the Higgs boson is a crucial component of the Higgs-boson physics programme at the LHC, since they probe potential new interactions with the Higgs boson introduced by possible extensions of the Standard Model. The $H \rightarrow \gamma \gamma$ Dalitz decay is particularly interesting in this respect as it is a loop process and the three-body final state allows the CP structure of the Higgs boson to be probed. However, the small expected signal-to-background ratio and the typically low dilepton invariant mass make the search for $H \rightarrow \gamma \gamma$ highly challenging.

The analysis performed by ATLAS searched for $H \rightarrow \ell^+\ell^-$ and $H \rightarrow \mu^+\mu^-$ decays. Special treatment was needed in particular for the electron channel: a dedicated electron trigger was developed as well as a specific identification algorithm. The predicted $m_\ell^2$ spectrum rises steeply towards lower values, with a kinematic cutoff at twice the final-state lepton mass. At such low electron-positron invariant masses, and given the large transverse momentum of their system, the electromagnetic showers induced by the electron and the positron in the ATLAS calorimeter can merge, requiring a specially developed reconstruction. Furthermore, a dedicated identification algorithm was developed for these topologies, and its efficiency was measured in data using photon detector-material conversions at low radius into an electron-positron pair from $Z \rightarrow e^+e^-$ events.

The signal extraction is performed by searching in the $\ell^+\ell^-$ invariant mass ($m_\ell^2$) range between 130 and 160 GeV for a narrow signal peak over smooth background at the mass of the Higgs boson. The sensitivity to the $H \rightarrow \gamma \gamma$ signal was increased by separating events in mutually exclusive categories based on lepton types and event topologies. ATLAS reports evidence in data for a $H \rightarrow \gamma \gamma$ signal emerging over the background with a significance of 3.2σ (see figure).

The Higgs boson production cross-section times branching fraction, measured for $m_\ell < 30$ GeV, amounts to $8.7^{+1.2}_{-1.2}$ fb. It corresponds to a signal strength—the ratio of the measured cross-section times branching fraction to the Standard Model prediction—of $1.5 \pm 0.5$. Meanwhile, ATLAS has also extended the invariant-mass range of the lepton pair for the related Higgs-boson decay into a photon and a Z boson to lower masses, opening the door to future studies of three-body Higgs-boson decays and investigations of its underlying CP structure.

Further reading

Fig. 1. Invariant mass of the $\ell^+\ell^-$ system, with every data event contributing a category-dependent weight representing the expected sensitivity of the $H \rightarrow \ell^+\ell^-$ signal. The data are shown as purple dots, while the lines show the signal and background functions as obtained by a fit.
Deep learning tailors supersymmetry searches

Supersymmetry is a popular extension of the Standard Model (SM) that has the potential to resolve several open questions in particle physics. As a result of a postulated new degree of freedom in the form of superpartners in the SM, one anticipates a compact and consistent framework that could make up dark matter, while adding new interactions that could be detectable in collider experiments. In the LHCb, the search for these superpartners, and in particular for charginos and neutralinos, is required for measuring some new physical parameters, and for mixing and CP violation measurements in the MSSM.

This work is based on the LHCb Collaboration's analysis of its data. The goal is to determine the branching fractions of the chargino and neutralino production, as well as branching fraction measurements of two important decays, B → τν and H → ττ. The results reduce the uncertainty on B → τν by roughly a factor of two for collisions at 7 TeV, and a factor of 5 for collisions at 13 TeV, yielding a precision of about 3%.

The theoretical uncertainties of the branching fractions are computed using the LHCb Collaboration's results. The systematic uncertainties are also considered, and the results are compared with the latest CMS measurements. The CMS Collaboration has reported results for B → τν with a precision of about 10%, while the LHCb Collaboration has improved the precision to about 3%.

Further reading
LHCb Collab. 2021 LHCb-PAPER-2020-046.

Precision leap for B_s fragmentation and decay

How likely is it for a b quark to partner itself with a light quark, creating a B_s meson? The answer depends on the momentum transfer, or d'quark, and the mass of the b quark. This question is key for understanding the physics of fragmentation and decay processes, which are fundamental in high-energy physics. In this context, a b quark can decay into a B_s meson, which then fragments into a hadron, such as a proton or a neutron.

In the LHCb Collaboration's analysis, the decay amplitude of B_s mesons is measured as a function of the momentum transfer, or d'quark, and the mass of the b quark. The results are obtained by comparing the measured decay rates with those predicted by the Leading Twistor Approximation (LTA) and the impulse approximation model. The results show that the LTA prediction is closer to the experimental data than the impulse approximation model.

Further reading
Reaching New Heights in Motion Technology

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FIELD NOTES

Reports from events, conferences and meetings

TOOLS 2020
Tooling up to hunt dark matter

The past century has seen ever stronger links forged between the physics of elementary particles and the universe at large. But the picture is mostly incomplete. For example, numerous observations indicate that 87% of the matter of the universe is dark, suggesting the existence of a new matter constituent. Given a plethora of dark-matter candidates, numerical tools are essential to advance our understanding. Fostering cooperation in the development of such software, the TOOLS 2020 conference attracted around 200 phenomenologists and experimental physicists for a week-long online workshop in November.

The viable mass range for dark matter spans 90 orders of magnitude, while the uncertainty about its interaction cross section with ordinary matter is even larger (see “Theoretical landscape” figure). Dark matter may be new particles belonging to theories beyond the Standard Model (BSM), an aggregate of new or SM particles, or very heavy objects such as primordial black holes (PBHs). On the latter subject, Jérémy Auffinger (IP2I Lyon) updated TOOLS 2020 delegates on codes for very light PBHs, noting that “BlackHawk” is the first open-source code for Hawking-radiation calculations.

Flourishing models
Weakly interacting massive particles (WIMPs) have enduring popularity as dark-matter candidates, and are amenable to search strategies ranging from colliders to astrophysical observations. In the absence of any clear detection of WIMPs at the electroweak scale, the number of models has flourished. Above the TeV scale, these include general hidden-sector models, FIMPs (feebly interacting massive particles), SIMPs (strongly interacting massive particles), super-heavy and/or composite candidates and PBHs. Below the GeV scale, these include the QCD axion, more generic ALPs (axion-like particles) and ultra-light bosonic candidates. ALPs are a class of models that received particular attention at TOOLS 2020, and are now being sought in fixed-target experiments across the globe.

For each dark-matter model, astroparticle physicists must compute the theoretical predictions and characteristic signatures of the model and confront those predictions with the experimental bounds to select the model parameter space that is consistent with observations. To this end, the past decade has seen the development of a huge variety of software – a trend mapped and encouraged by the TOOLS conference series, initiated by Fawzi Boudjema (LAPTh Annecy) in 1999, which has brought the community together every couple of years since.

Three continuously tested codes currently dominate generic BSM dark-matter model computations. Each allows for the computation of relic density from freeze-out and predictions for direct and indirect detection, often up to next-to-leading corrections. Agreement between them is kept below the percentage level. “micrOMEGAs” is by far the most used code, and is capable of predicting observables for any generic model of WIMPs, including those with multiple dark-matter candidates. “DarkSUSY” is more oriented towards supersymmetric theories, but it can be used for generic models as the code has a very convenient modular structure. Finally, “MadDM” can compute WIMP observables for any BSM model from MeV to hundreds of TeV. As MadDM is a plugin of MadGraph, it inherits unique features such as its automatic computation of new dark-matter...
Models connecting dark matter with collider experiments are becoming ever more optimised to the needs of users. Just a few. Freeze-in is now supported by recent micromegas analyses of Higgsino dark matter. Models connecting dark matter with collider experiments are becoming ever more optimised to the needs of users. As MadDM is embedded in Madgraph, noted Benjamin Fuku (LPTHE Paris), tools such as MadAnalysis may be used to recast CMS and ATLAS searches. Celine Degrande (UCLouvain) described another nice tool, FeynRules, which produces model files in both the MadDM and micromegas formats given the Lagrangian for the ISDM model, providing a very useful automated chain from the model directly to the dark-matter observables, high-energy predictions and comparisons with experimental results. Meanwhile, MadDrupups Madgraph’s predictions and detector simulations from the high-energy physics community are available in the framework of multi-messenger physics. It is an excellent project for an exascale problem.

Quark–matter fireballs hashed out in Protvino

The XXXII international workshop of the Logunov Institute for High-Energy Physics of the NRC Kurchatov Institute in Protvino, near Moscow, brought more than 500 physicists together online from 9 to 13 November to discuss “hot problems in hot and cold quark matter”. The focus of the workshop was chiral effective theories and lattice simulations, which allow estimates beyond perturbation theory for studying strongly interacting matter that are probed in heavy-ion collisions and deconfined matter, as well as B the tidal deformabilities of merging neutron stars and the peak frequency of the emitted gravitational waves. Several participants observed that tidal deformabilities are measured in the inspiral phase, and the peak gravitational-wave frequency is measured in the post-merger phase, which may together reveal the state of a neutron–star interior. Mergers observed since 2017 may already be able to shed light on the existence of a deconfined phase inside these ultra-compact objects.

The workshop revealed the enduring importance of studying heavy–quark physics.
Experiments such as MADMAX, IAXO and ALPS II are expanding the search for axions and other weakly interacting ‘slim’ particles that could hail from far above the TeV scale, write Axel Lindner, Béla Majorovits and Andreas Ringwald. 

The Standard Model (SM) cannot be the complete theory of particle physics. Neutrino masses evade it. No viable dark-matter candidate is contained within it. And under its auspices the electric dipole moment of the neutron, experimentally compatible with zero, requires the cancellation of two non-vanishing SM parameters that are seemingly unrelated — the strong-CP problem. The physics explaining these mysteries may well originate from new phenomena at energy scales inaccessible to any collider in the foreseeable future. Fortunately, models involving such scales can be probed today and in the next decade by a series of experiments dedicated to searching for very weakly interacting slim particles (WISPs).

WISPs are pseudo Nambu–Goldstone bosons (pNGBs) that arise automatically in extensions of the SM from global symmetries which are broken both spontaneously and explicitly. NGBs are best known for being “eaten” by the longitudinal degrees of freedom of the W and Z bosons in electroweak gauge-symmetry breaking, which underpins the Higgs mechanism, but theorists have also postulated a bevy of pNGBs that get their tiny masses by explicit symmetry breaking and are potentially discoverable as physical particles. Typical examples arising in theoretically well-motivated grand-unified theories are axions, flavons and majorons. Axions arise from a broken “Peccei–Quinn” symmetry and could potentially explain the strong-CP problem, while flavons and majorons arise from broken flavour and lepton symmetries.

Being light and very weakly interacting, WISPs would be non-thermally produced in the early universe and thus remain non-relativistic during structure formation. Such particles would inevitably contribute to the dark matter of the universe. WISPs are now the target of a growing number and type of experimental searches that are complementary to new-physics searches at colliders.

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Among theorists and experimentalists alike, the axion is probably the most popular WISP. Recently, massive efforts have been undertaken to improve the calculations
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Haloscope home: The Morpurgo magnet in CERN's North Area, which will house a prototype MADMAX haloscope.

The field of play

Limits (solid lines), projected sensitivities (dashed lines) and hints and projections (hashed areas) in the axion–photon coupling (\(g_A\)) versus axion mass (\(m_a\)) plane. The axion obtains its mass through mixing with the axion-like particle (ALPs), the parameter range is even broader. With many plausible relic–ALP–production mechanisms proposed by theorists, experimentalists need to cover as much of the unexplored parameter range as possible.

Although the strengths of the interactions between axions or ALPs and SM particles are very weak, being inversely proportional to \(\mu\), several strategies for observing them are available. Limits and projected sensitivities span several orders of magnitude in the mass–coupling plane (see “The field of play” figure).

Since axions or ALPs can usually decay to two photons, an external static magnetic field can substitute one of the two photons and induce axion-to-photon conversion. Originally proposed by Pierre Sikivie, this inverse Primakoff effect can classically be described by adding source terms proportional to \(B\) and \(R\) to Maxwell’s equations. Practically, this means that inside a static homogeneous magnetic field the presence of an axion or ALP field induces electric-field oscillations – an effect readily exploited by many experiments searching for WISPs. Other processes exploited in some experimental searches and suspected to lead to axion production are their interactions with electrons, leading to axion bremsstrahlung, and their interactions with nucleons or nuclei, leading to nucleon–axion bremsstrahlung or oscillations of the electric dipole moment of the nuclei or nucleons.

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The clean technology innovations solving challenges in particle physics

Particle physics laboratories across Europe are pushing the frontiers of science and technology every day. To help them excel, they need a cleanroom partner that can resolve contamination issues in new, innovative ways. Over the years, C2C (Connect 2 Cleanrooms) has supported research organizations across Europe with cleanroom projects, partnering with CERN, STFC and ESS to find innovative solutions to support the R&D, build, commissioning and maintenance of particle accelerators.

Part of CERN’s Prevessin site in France is dedicated to producing beam intercepting devices, used in different particle accelerators across its world-leading particle physics laboratory. This involves the assembly of highly specialised parts such as collimators to clean the halo of proton beams, beam stoppers and beam dumps to absorb the energy of particles. These beam intercepting devices are built in sections to allow parts to be decommissioned and removed for servicing and maintenance.

With these highly calibrated pieces of machinery, there is a risk that exposed parts could be effected by particulate contamination during assembly or servicing. Even a small amount of contamination inside the chamber could affect how the beam is travelling and render them ineffective. Conducting the assembly inside a cleanroom, which has a high air change rate of high efficiency particulate air (HEPA), would greatly reduce the risk of particulate contamination. However, as some of these parts are up to 5 metres long and 30 tonnes in weight, transportation is only possible by road or rail. The real challenge then, is how in these parts would be transferred into a cleanroom.

A telescopic solution

Although on a different scale, C2C have innovated to overcome a similar challenge previously. C2C’s R&D team developed an adjustable modular cleanroom system that could be slided back, giving overhead crane access to the tunnel as there are fewer restrictions on space and the ability to remove parts for servicing and maintenance.

When the larger beam intercepting device sections have been craned into the servicing bay, the cleanroom can be expanded to the laterally envelope the part. The modules extend on guide rails from a closed position to triple the floor space. When in the closed position the cleanroom can be used for work on smaller parts, which means all the beam intercepting device components can be assembled in the same environment.

The softwall cleanroom is designed to maintain the air cleanliness and quality. It achieves particle counts to maintain ISO 14644-1 class 6 when in the extended position, and in the closed position it achieves particle counts to meet ISO 14644-1 class 6.

“Connect 2 Cleanrooms was the most competitive partner who passed our tender evaluation criteria,” says Oliver Aberle, project manager at CERN. “The design stage was very fast and the principle of the layout was complete within the first iteration. The end result is unique when you see the extending cleanroom in motion.”

STFC & ESS’s mobility challenge

Science and Technology Facilities Council (STFC) is a world-leading science organisation that supports research in development in many disciplines, including particle physics. C2C has engineered numerous contamination control solutions for STFC, to meet their niche requirements and in 2018 were appointed to complete a project they were delivering for the European Spallation Source (ESS) in Sweden. These cleanrooms are now facilitating the build and operation of the particle accelerator which will be the world’s most powerful neutron source, enabling scientific breakthroughs in research.

The particle accelerator is being built in sections at ESS facilities in Lund, Sweden. Each section is initially built outside of the tunnel as there are fewer restrictions on space and better access to infrastructure, once completed, the sections are then checked and sealed before being transported down the tunnel.

C2C developed mobile cleanrooms that maintain ISO 14644-1 class 5 conditions and are used to provide end-to-end protection covering the build, transportation within the tunnel and the interconnection of different accelerator sections. The size of the tunnel presented a challenge for the mobile cleanrooms. With an overall height of 4 metres, the services needed to operate the accelerator at points bring the height down to 3.5 metres. In addition, STFC requested the mobile cleanroom to be in three distinct sections that can operate independently and be connected together when in position. One section is height adjustable so that it can move freely under the services, then be adjusted to a full height when in position.

C2C worked to STFC’s User Specification to design a cleanroom that can be adapted to different sizes. The cleanroom is designed to be scalable to the higher axion-mass regions as preferred, for example, by cosmological models where Peccei–Quinn symmetry breaking happened after an inflationary phase of the universe. That’s where MADMAX comes in. The collaboration is working on the dielectric–haloscope concept – initiated and led by scientists at the Max Planck Institute for Physics in Munich – to investigate the mass region around 100 µeV.

**Prototype Conceptual design of the BabyADX haloscope, which will seek to observe axion-like particles**

**Astrophysical hints**

Weakly interacting slim particles (WISPs) could be produced in high energy astrophysical plasmas and transport energy out of stars, including the Sun, stellar remnants and other dense sources. Observed lifetimes and energy-loss rates can therefore probe their existence. For the axion, or an axion-like particle (ALP) with sub-MeV mass that couples to nucleons, the most stringent limit, $f_A > 10^{16}$ GeV, stems from the duration of the neutrino signal from the progenitor neutron star of Supernova 1987A.

Tantalisingly, there are still hints from observations of red giants, Herbig–Haro, white dwarfs and pulsars that seem to indicate energy losses with slight excesses below 100 meV or sub-keV–mass ALPs with a coupling to both electrons and photons. Other observations suggest that UV photons from distant blazars are less absorbed than expected by standard interactions with extragalactic background light – the so-called transparency hint. This could be explained by the conversion of photons into ALPs in the magnetic field of the source, and back to photons in astrophysical magnetic fields.

Interestingly, these would have about the same ALP photons-coupling strength as indicated by the observed stellar anomalies, though with a mass that is incompatible with both ALPs which can explain dark matter and with QCD axions (see “The field of play” figure, p27).

**Connect 2 Cleanrooms**

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### FEATURE WEAKLY INTERACTING SLIM PARTICLES

In the overlapping mass region up to 0.1 meV, the sensitivities of ALPS II and BabyIAXO are roughly equal. In the event of a discovery, this would provide a unique opportunity to study the new WISP. Excitingly, a similar case might be realised for IAXO, combining the optics and detectors of ALPS II with simplified versions of the dipole magnets being studied for FCC-hh. This would provide an LSW experiment with “IAXO sensitivity” regarding the axion-photon coupling, albeit in a reduced mass range. This has been outlined as the putative JURA (Joint Undertaking on Research for Axions) experiment in the context of the CERN-led Physics Beyond Colliders study.

The past decade has delivered significant developments in axion and ALP theory and phenomenology. This has been complemented by progress in experimental methods to cover a large fraction of the interesting axion and ALP parameter range. In close collaboration with universities and institutes across the globe, CERN, DESY and the Max Planck society will together pave the road to the exciting results that are expected this decade.

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RUSSIA’S PARTICLE-PHYSICS POWERHOUSE

Fifty years after being established, the Institute for Nuclear Research in Moscow continues to leave its mark on neutrino and high-energy physics.

Founded on 24 December 1970, the Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS) is a large centre for particle physics in Moscow with wide participation in international projects. The INR RAS conducts work on cosmology, neutrino physics, astrophysics, high-energy physics, accelerator physics and technology, neutron research and nuclear medicine. It is most well-known for its unique research facilities that are spread all across Russia, and its large-scale collaborations in neutrino and high-energy physics. This includes experiments such as the Baksan Neutrino Observatory, and collaborations with a number of CERN experiments including CMS, ALICE, LHCb, NA61 and NA64.

The institute was founded by the Decree of the Presidium of the USSR Academy of Sciences in accordance with the decision of the government. Theoretical physicist Moisey Manolov had a crucial role in establishing the institute and influenced the research that would later be undertaken. His aim is seen in the decision to base INR RAS on three separate nuclear laboratories of the P.N. Lebedev Institute of Physics of the Academy of Sciences of the USSR. Each laboratory had a leading physicist in charge: the Nuclear Physics Laboratory headed by Nobel laureate Ilya Frank; the Photoneutron Reactions Laboratory under the direction of Lyubov Lazareva; and a neutrino laboratory headed by Georgy Zatsepin and Alexander Chudakov. The man overseeing it all was the first director of INR RAS, Albert Tavkhelidze, a former researcher at the Joint Institute for Nuclear Research (JINR, Dubna). In 1987 Victor Matveev took over as director, followed by Leonid Kravchuk in 2014. Since 2020 the director of INR RAS is Maxim Libanov.

From the very beginning, major efforts were focused on the construction and operation of large-scale research facilities. The hub of INR RAS was built 20 km outside of Moscow, in a town called Troitsk. In 1971 an accelerator division was created, with a long-term goal of creating a meson facility that would house a 600 MeV linear accelerator for protons and H⁻ ions. The first beam was eventually accelerated to 20 MeV in 1988 and the facility was fully operational by 1993. Now known as the Moscow Meson Facility, it has the most powerful linear proton accelerator in the Euro-Asian region, providing fundamental research facilities that first directly observed neutrinos from supernova SN1987A.

Ice breaker New clusters of optical modules being installed in the underwater Baikal-GVD Neutrino Telescope in April 2020.

and applied research in nuclear and neutrino physics, condensed matter, development of technologies for the production of a wide range of radioisotopes, operation of a radiation therapy complex and many other applications.

A town called Neutrino Over 1000 miles south from the Troitsk laboratory, an underground tunnel in the Caucasus mountains is the base of another INR RAS facility, the Baksan Neutrino Observatory (BNO). The facility was established in 1967 and the Baksan Underground Scintillation Telescope (BUST) started taking data in 1978. A town sensibly called “Neutrino” (Russian for neutrino) was constructed in parallel with the facility, and was where scientists and their families could live 1700 m above sea level next to the observatory. In 1987 BUST was one of the four neutrino detectors that first directly observed neutrinos from supernova SN1987A.

The observatory did not finish there, and the next step
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The future of INR RAS is deeply rooted in its new global reach, the first ever brane-world models and the development of principles and the search for mechanisms for the formation of the baryon asymmetry of the universe.

Global Reach

Scientists from INR RAS take an active part in the work of a number of large international experiments at CERN, JINR, and in Germany, Japan, Italy, USA, China, France, Spain and other countries. The institute also conducts educational activities, having its own graduate school and teaching departments in nearby institutes such as the Moscow Institute for Physics and Technology.

The future of INR RAS is deeply rooted in its new large-scale infrastructures. Baikal-OVD will, along with the IceCube experiment at the South Pole, be able to register neutrinos of astrophysical origin in the hope of establishing their nature. A project has been prepared to modernise the linear proton accelerator in Troitsk using superconducting radio-frequency cavities, while there are also plans to construct a large centre for nuclear medicine based at the linear accelerator centre. There is a proposal to build the Baksan Large Volume Scintillator Detector at BNO containing 10 tons of ultra-pure liquid scintillator, which would be able to register neutrinos from the carbon–nitrogen–oxygen (CNO) fusion cycle in the Sun with a precision sufficient to discriminate between various solar models.

The past 50 years have seen consistent growth at INR RAS, and with world-leading future projects on the horizon, the institute shows no signs of slowing down.
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The ability to collide high-energy beams of hadrons under controlled conditions transformed the field of particle physics. Until the late 1960s, the high-energy frontier was dominated by the great proton synchrotrons. The Cosmotron at Brookhaven National Laboratory and the Bevatron at Lawrence Berkeley National Laboratory were soon followed by CERN’s Proton Synchrotron and Brookhaven’s Alternating Gradient Synchrotron, and later by the Proton Synchrotron at Serpukov near Moscow. In these machines, protons were directed to internal or external targets in which secondary particles were produced.

The kinematic inefficiency of this process, whereby the centre-of-mass energy only increases as the square root of the beam energy, was recognised from the outset. In 1963, Norwegian engineer Rolf Widerøe proposed the idea of colliding beams, keeping the centre of mass at rest in order to exploit the full energy for the production of new particles. One of the main problems was to get colliding beam intensities high enough for a useful event rate to be achieved. In the 1960s the prolific group at the University of Wisconsin Midwestern Universities Research Association (MURA), led by Donald Kerst, worked on the problem of “stacking” particles, whereby successive pulses from an injector synchrotron are superposed to increase the beam intensity. They mainly concentrated on protons, where Liouville’s theorem (which states that for a continuous fluid under the action of conservative forces the density of phase space cannot be increased) was thought to apply. Only much later, ways to beat Liouville and to increase the beam density were found. At the 1966 International Accelerator Conference at CERN, Kerst made the first proposal to use stacking to produce colliding beams (not yet storage rings) of sufficient intensity.

At that same conference, Gerry O’Neill from Princeton presented a paper proposing that colliding electron beams could be achieved in storage rings by making use of the natural damping of particle amplitudes by synchrotron-radiation emission. A design for the 500 MeV Proton–Proton storage ring experiment was published in 1965 and construction started that same year. At the same time, the Budker Institute for Nuclear Research in Novosibirsk started work on VEPP-1, a pair of rings designed to collide electrons at 340 MeV. Then, in March 1966, Bruno Touschek gave a seminar at Laboratori Nazionali di Frascati in Italy where he first proposed a fixed-target proton–proton collider. “AdA” produced the first stored electron and positron beams less than a year later – a far cry from the time it takes today’s machines to go from conception to operation! From these trailblazers evolved the production machines, beginning with ADONE at Frascati and SPEAR at SLAC. However, it was always clear that the gift of synchrotron-radiation damping would become a hindrance to achieving very high energy collisions in a circular electron–positron collider because the power radiated increases as the square of the beam energy and the inverse fourth power of mass, so is negligible for protons compared with electrons.

A step into the unknown

Meanwhile, in the early 1960s, discussion raged at CERN about the next best step for particle physics. Opinion was sharply divided between two camps, one pushing a very high-energy proton synchrotron for fixed-target physics and the other using the technique proposed at MURA to build an innovative colliding beam proton machine with about the same centre-of-mass energy as a conventional proton synchrotron of much larger dimensions. In order to resolve the conflict, in February 1966, 50 physicists from among Europe’s best met at CERN. From that meeting emerged a new committee, the European Committee for Future Accelerators, under the chairmanship of one of CERN’s founding fathers, Edoardo Amaldi. After about two years of deliberation, consensus was formed. The storage ring gained most support, although a high-energy proton synchrotron, the Super Proton Synchrotron (SPS), was built some years later and would go on to play an essential role in the development of hadron storage rings. On 15 December 1965, with the strong support of Amaldi, the CERN Council unanimously approved the construction of the Intersecting Storage Rings (ISR), launching the era of hadron colliders.

First collisions

Construction of the ISR began in 1966 and first collisions were observed on 27 January 1971. The machine, which needed to store beams for many hours without the help of synchrotron-radiation damping to combat inevitable magnetic field errors and instabilities, pushed the boundaries in accelerator science on all fronts. Several respected scientists doubted that it was a feasible machine. In fact, the ISR worked beautifully, exceeding its design luminosity by an order of magnitude and providing an essential step in the development of the next generation of hadron colliders to apply. A key element was the performance of its ultra-high-vacuum system, which was a source of continuous improvement throughout the 13-year-long lifetime of the machine.

For the experimentalists, the ISR’s collisions (which reached an energy of 6 GeV) opened an exciting adventure at the energy frontier. But they were also learning what kind of detectors to build to fully exploit the potential of the machine – a task made harder by the lack of clear physics benchmarks known at the time in the ISR energy regime. The concept of general-purpose instruments built by large collaborations, as we know them today, was not in the culture of the time. Instead, many small collaborations built experiments with relatively short lifecycles, which constituted a fruitful learning ground for what was to come at the next generation of hadron colliders.

There was initially a broad belief that physics action would be in the forward directions at a hadron collider. This led to the Split Field Magnet facility as one of the first detectors at the ISR, providing a high-momentum in the forward directions but a negligible one at large angle with respect to the colliding beams (the nowadays so-important transverse direction). It was with subsequent detectors featuring transverse spectrometer arms over limited...
solid angles that physicists observed a large excess of high transverse momentum particles above low-energy extrapolations. With these first observations of point-like parton scattering, the ISR made a fundamental contribution to strong-interaction physics. Solid angles were too limited initially, and single-particle triggers too biased, to fully appreciate the hadronic jet structure. That feat required third-generation detectors, notably the Axial Field Spectrometer (AFS) at the end of the ISR era, offering full azimuthal central calorimeter coverage. The experiment provided evidence for the back-to-back two-jet structure of hard parton scattering.

For the detector builders, the original AFS concept was interesting as it provided an unobstructed, phi-symmetric magnetic field in the centre of the detector, however, at the price of massive Helmholtz coils pale topic obstructing the foreground directions. Indeed, the ISR enabled the development of many original experimental ideas. A very important one was the measurement of the total cross section using the back-to-back two-jet structure of hard parton scattering. The experiment provided evidence for the back-to-back two-jet structure of hard parton scattering.


The ISR in 1972, the phenomenon of Schottky noise (density fluctuations due to the granular nature of the beam in a storage ring) was first observed. It was this very same noise that Simon van der Meer speculated in a paper a few years earlier could be used for what he called “stochastic cooling” of a proton beam, bearing LIGO’s theorem by the fact that a beam of particles is not a continuous fluid. Although it is unrealistic to detect the motion of individual particles and damp them to the nominal orbit, van der Meer showed that by correcting the mean transverse motion of a sample of particles continuously, and as long as the statistical nature of the Schottky signal was continuously regenerated, it would be theoretically possible to reduce the beam size and increase its density. With the bandwidth of electronics available at the time, van der Meer concluded that the cooling time would be too long to be of practical importance. But the challenge was taken up by Wolfgang Schnell, who built a state-of-the-art feedback system that demonstrated stochastic cooling of a proton beam for the first time. This would open the door to the idea of stacking and cooling of antiprotons, which later led to the SPS being converted into a proton–antiproton collider.

Another important step towards the next generation of hadron colliders occurred in 1973 when the collaboration working on the Gargamelle heavy liquid bubble chamber published two papers revealing the first evidence for weak neutral currents. These were important observations in support of the unified theory of electromagnetic and weak interactions, for which Sheldon Glashow, Abdus Salam and Steven Weinberg were to receive the Nobel Prize in Physics in 1979. The electroweak theory predicted the existence and approximate masses of two vector bosons, the W and the Z, which were too high to be produced in any existing machine. However, Carlo Rubbia and collaborators proposed that, if the SPS could be converted into a collider with protons and antiprotons circulating in opposite directions, there would be enough energy to create them.

To achieve this the SPS would need to be converted into a storage ring like the ISR, but this time the beam would need to be kept “bunched” with the radio–frequency (RF) system working continuously to achieve a high enough luminosity (unlike the ISRs where the beams were allowed to de-bunch all around the ring). The challenges here were two–fold. Noise in the RF system causes particles to diffuse rapidly from the bunch. This was solved by a dedicated feedback system. It was also predicted that the beam–beam interaction would limit the performance of a bunched–beam machine with no synchrotron–radiation damping due to the strongly nonlinear interactions between a particle in one beam with the global electromagnetic field in the other beam.

A much bigger challenge was to build an accumulator ring in which antiprotons could be stored and cooled by stochastic cooling until a sufficient intensity of antiprotons would be available to transfer into the SPS, accelerate to around 900 GeV in collision with protons. This was done in two stages. First a proof–of–principle was needed to show that the ideas developed at the ISR transferred to a dedicated accumulator ring specially designed for stochastic cooling. This ring was called the Initial Cooling Experiment (ICE), and operated at CERN in 1977–1978. In ICE stochastic cooling was applied to reduce the size and a new technique for reducing the momentum spread in the beam was developed. The experiment proved to be a huge success and stochastic cooling was refined to a point where a real accumulator ring (the Antiproton Accumulator) could be designed to accumulate and store antiprotons produced at 3.5 GeV by the proton beam from the 26 GeV Proton Synchrotron. First collisions of protons and antiprotons at 270 GeV were observed on the night of 10 July 1978, signalling the start of a new era in colliding beam physics.

A clear physics goal, namely the discovery of the W and Z intermediate vector bosons, drove the concepts for the two main SPS experiments at the ISR. CERN and UA1 in 1977, and UA2 (in addition to UA1) in 1978. The lack of hermeticity in the central part of the FERMILAB–SPP–S experiments because of its inherent lack of azimuthal symmetry. UA2 featured a (at the time) highly segmented electromagnetic and hadronic calorimeter in the central part (down to 40 degrees with respect to the beam axis), with 240 cells pointing to the interaction region. But it had no muon detection, and in its initial phase only limited electromagnetic coverage in the forward regions. There was no magnetic field except for the forward cones with toroids to probe the W polarisation.

In 1978 the SPS experiments made history with the direct discoveries of the W and Z. Many other results were obtained, including the first evidence of neutral B–meson particle–antiparticle mixing at UA1, thanks to its track– and muon detection. The calorimeter of UA2 provided immediate unambiguous evidence for a two–jet structure in events with large transverse energy. Both UA1 and UA2 pushed QCD studies far ahead. The lack of hermeticity in UA2′s forward regions motivated a major upgrade (UA2′) for the second phase of the collider, complementing the central part with new fully hermetic calorimetry (both electromagnetic and hadronic), and also inserting a new tracking cylinder employing novel technologies (three track– and silicon pad detectors). This enabled the experiment to improve searches for top quarks and supersymmetric particles, as well as making almost background–free first precision measurements of the W mass.

First steps
The SPS was driving new studies at CERN, the first large superconducting synchrotron (the Pwetsron, with a design energy close to 1 TeV) was under construction at Fermilab. In view of the success of the stochastic cooling experiments, there was a strong lobby at the time to halt the construction of the Pwetsron and divert effort instead to emulate the SPS as a proton–antiproton collider using the Fermilab Main Ring. Wisely this proposal was rejected.
Chasing bosons

The USA detector at the Spp–S.

and construction of the Tevatron continued. It came into operation as a fixed-target synchrotron in 1984. Two years later it was also converted into a proton–antiproton collider and operated at the high-energy frontier until its closure in September 2011.

A huge step was made with the detector concepts for the Tevatron experiments, in terms of addressed physics signatures, sophistication and granularity of the detector components. This opened new and continuously evolving avenues in analysis methods at hadron colliders. Already in September 2011.

Following repairs and consolidation, on 29 November 2009, a major constraint was the small (3.8 m) tunnel diameter, which made it impossible to house two independent rings in the tunnel in which the machine was to be housed. For the LHC to achieve its design energy of 7 TeV per beam, its bending magnets would need to operate at a field of 8.3 T, about 60% higher than ever achieved in previous machines. This could only be done using affordable superconducting material by reducing the temperature of the liquid-helium coolant from its normal boiling point of 4.2 K to 1.9 K – where helium exists in a macroscopic quantum state with the loss of viscosity and a very large thermal conductivity. A second major constraint was the small (1.8 m) tunnel diameter, which made it impossible to house two independent rings like the ISR. Instead, a novel and elegant magnet design, first proposed by Bob Palmer at Brookhaven, with the two rings separated by only 19 cm in a common yoke and cryostat was developed. This also considerably reduced the cost.

At precisely 09:30 on 10 September 2008, almost 15 years after the project’s approval, the first beam was injected into the LHC, and many of the contributors at CERN and elsewhere were able to watch the collision on a live screen. The LHC experiments are a whole other level of sophistication was realised by the LHC detectors compared to those at previous colliders. The priority benchmark for the designs of the general-purpose detectors ATLAS and CMS was to unambiguously discover (or rule out) the Standard Model Higgs boson for all possible masses up to 1 TeV, which demanded the ability to measure a variety of final states. The challenges for the Higgs search also guaranteed the detectors’ potential for all kinds of searches for physics beyond the Standard Model, which was the other driving physics motivation at the energy frontier. These two very ambitious LHC detector designs integrated all the lessons learned from the experiments at the three predecessor machines, as well as further technology advances in other large experiments, most notably at HERA and LEP. Just a few simple numbers illustrate the giant leap from the Tevatron to the LHC detectors: CDF and D0, in their upgraded versions operating at a luminosity of up to...
This journey is now poised to continue, as we look ahead towards how a general-purpose detector at a future 100 TeV hadron collider might look like that there are no strict boundaries between these three physics fields for them. All of them have learned to use features of their instruments to contribute at least in part to the full physics spectrum offered by the LHC, of which the highlight so far was the July 2012 announcement of the discovery of the Higgs boson by the ATLAS and CMS collaborations. The following year the collaborations were named in the citation for the 2013 Nobel Prize in Physics awarded to François Englert and Peter Higgs. Since then, the LHC has exceeded its design luminosity by a factor of two and delivered an integrated luminosity of almost 20 fb⁻¹ in proton–proton collisions, while its beam energy was increased to 5.5 TeV in 2015. The machine has also delivered heavy ion (lead–lead) and even lead–proton collisions. But the LHC still has a long way to go before its estimated end of operations in the mid- to late 2030s. To this end, the machine was shut down in November 2018 for a major upgrade of the whole of the CERN injector complex as well as the detectors to prepare for operation at high luminosities, ultimately up to a “levelled” luminosity of 7×10^34 cm⁻²s⁻¹. The High Luminosity LHC (HL-LHC) upgrade is pushing the boundaries of superconducting magnet technology to the limit, particularly around the experiments where the present focusing elements will be replaced by new magnets built from high-performance Nb₃Sn superconductor. The eventual objective is to accumulate 3000 fb⁻¹ of integrated luminosity.

In parallel, the LHC–experiment collaborations are preparing and implementing major upgrades to their detectors using novel state-of-art technologies and revolutionary approaches to data collection to exploit the tenfold data volume promised by the HL-LHC. Hadron–collider detector concepts have come a long way in sophistication over the past 50 years. However, behind the scenes are other factors paramount to their success. These include an equally spectacular evolution in data-flow architectures, software and the computing approaches and analysis methods – all of which have been driven into new territories by the extraordinary needs for dealing with rare events within the huge backgrounds of ordinary collisions at hadron colliders. Worthy of particular mention is the success of all LHC physics results is the Worldwide LHC Computing Grid. This journey is now poised to continue, as we look ahead towards how a general-purpose detector at a future 100 TeV hadron collider might look like.

Beyond the LHC

Although the LHC has at least 15 years of operations ahead of it, the question now arises, as it did in 1964, what is the next step for the field? The CERN Council has recently approved the recommendations of the 2020 update of the European strategy for particle physics, which includes, among other things, a thorough study of a very-high-energy hadron collider to succeed the LHC. A technical and financial feasibility study for a 100 km circular collider at CERN with a collision energy of at least 100 TeV is now under way. While a decision to proceed with such a facility is to come later this decade, one thing is certain: lessons learned from 50 years of experience with hadron colliders and their detectors will be crucial to the success of our next step into the unknown.
A DECADE IN LHC PUBLICATIONS

The first 10 years of LHC operations have generated a bumper crop of new knowledge.

2852 papers from experiment. From the first publications in 2008 that described the detector designs, through 2012’s discovery of the Higgs boson, all the way to CMS’s 1000th publication in 2020.

In June 2020, the CMS collaboration submitted a paper titled “Observation of the production of three massive gauge bosons, $\gamma Z' T W'$” to the arXiv preprint server. A scientific highlight in its own right, the paper also marked the collaboration’s thousandth publication. ATLAS is not far from reaching the same milestone, currently at 964 publications (data correct as of 7 January). With the rest of the LHC experiments taking the total number of papers to 2852, the first 10 years of LHC operations have generated a bumper crop of new knowledge.

The publication landscape in high-energy physics (HEP) is exceptional due to a long-held preprint culture. At CERN, paper copies were kept in cabinets outside the library from 1984 until 2018, when the LHC experiment operations took the total number of papers to 2852, the first 10 years of LHC operations have generated a bumper crop of new knowledge.

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Connecting physics with society

Audiences never look at particle physics with the same eyes once they’ve learned about its wider applications, says Barbora Bruant Gulejova

Science and basic research are drivers of technologies and innovations, which in turn are key to solving global challenges such as climate change and energy. The United Nations has summarised these challenges in 17 ‘sustainable development goals’, but it is striking how little connection with science they include.

Furthermore, as found by a UNESCO study in 2017, the interest of the younger generation in studying science, technology, engineering and mathematics is falling, despite jobs in these areas growing at a rate three times faster than in any other sector. Clearly, there is a gulf between scientists and non-scientists when it comes to the perception of the importance of fundamental research in their lives – to the detriment of us all.

Try asking your neighbours, kids, family members or mayor of your city whether they know about the medical and other applications that come from particle physics, or the stream of highly qualified people trained at CERN who bring their skills to business and industry. While the majority of young people are attracted to physics by its mind-boggling findings and intriguing open questions, our subject appeals even more when individuals find out about its usefulness outside academia. This was one of the key outcomes of a recent survey, Chairing Ambassador for X in a mayor’s office, organised by the International Particle Physics Outreach Group (IPPOG).

Do most “Cernois” even know about the numerous start-ups based on CERN technologies or the hundreds of technology disclosures from CERN, 31 of which came in 2019 alone? Or about the numerous success stories contained within the CERN Impact brochure and the many resources of CERN’s knowledge-transfer group? Even though “impact” is gaining attention, accidentally when I presented these facts to my research colleagues they were not fully aware. Yet who else will be our ambassadors, if not us?

Some in the community are resistant to communicate physics spin-offs because this is not our primary purpose. Yet, millions of people who have lost their income as a result of COVID-19 are rather more concerned about where their next rent and food payments are coming from, than they are about the couplings of the Higgs boson. Reaching out to non-physicists is more important than ever, especially to those with an indifferent or even negative attitude to science. Differentiating audiences between students, general public and politicians is not relevant when addressing non-scientists and educated people. Strategic information should be proactively communicated to all stakeholders in society in a relatable way, via eye-opening, surprising and emotionally charged stories about the practical applications of curiosity-driven discoveries.

IPPOG has been working to provide such stories since 2017 – and there is no shortage of examples. Take the touch-screen technology first explored at CERN 40 years ago, or humanitarian satellite mapping carried out for almost 20 years by UNOSAT, which is hosted at CERN. Millions of patients are diagnosed daily thanks to tools like PET and MRI, while more recent medical developments include Innovative radiotopes from MEDICIS for precision medicine, the first 3D colour X-ray images, and now cancer treatments based on superconducting accelerators.

Credibility and trust in science can only be built by scientists themselves, while working hand in hand with professional communicators, but not relying only on them. Extracurricular activities, such as those offered by IPPOG, CERN, other institutions and individual initiatives, are crucial in changing the misperceptions of the public and bringing about fact-based decision-making to the young generation. Scientists should develop a proactive strategic approach and even consider becoming active in policy making, following the shining examples of those who helped realise the SESAME light source in the Middle East and the South East European International Institute for Sustainable Technologies.

Particle physics already inspires some of the brightest minds to enter science. But audiences never look at our subject with the same eyes once they’ve learned about its applications and science-for-peace initiatives.
INTERVIEW

How did winning a Special Breakthrough Prize last year compare with the Nobel Prize?

It came as quite a surprise because as far as I know, none of the people who have been honoured with the Breakthrough Prize had already received the Nobel Prize. Of course nothing compares with the Nobel Prize in prestige, if only because of the long history of great scientists to whom it has been awarded in the past. But the Breakthrough Prize has its own special value to me because of the calibre of the young – well, I think of them as young – theoretical physicists who are really dominating the field and who make up the selection committee.

The prize committee stated that you would be a recognised leader in the field even if you hadn't made your seminal 1967 contribution to the genesis of the Standard Model. What do you view as Weinberg's greatest hits?

There's no way I can answer that and maintain modesty! That work on the electroweak theory leading to the mass of the W and Z, and the existence and properties of the Higgs, was certainly the biggest splash. But it was rather untypical of me. My style is usually not to propose specific models that will lead to specific experimental predictions, but rather to interpret in a broad way what is going on and make very general remarks, like with the development of the point of view associated with effective field theory. Doing this I hope to try and change the way my fellow physicists look at things, without usually proposing anything specific. I have occasionally made predictions, some of which actually worked, like calculating the pion–nucleon and pion–pion scattering lengths in the mid-1960s using the broken symmetry that had been proposed by Nambu. There were other things, like raising the whole issue of the cosmological constant before the discovery of the accelerated expansion of the universe. I worried about that – I gave a series of lectures at Harvard in which I finally concluded that the only way I can understand why there isn't an enormous vacuum energy is because of some kind of anthropic selection. Together with two guys here at Austin, Paul Shapiro and Hugo Martel, we worked out what was the most likely value that would be found in terms of order of magnitude, which was later found to be correct. So I was very pleased that the Breakthrough Prize acknowledged some of those things that didn’t lead to specific predictions but changed a general framework.

You coined the term effective field theory (EFT) and recently inaugurated the online lecture series All Things EFT. What is the importance of EFT today?

My thinking about EFTs has always been in part conditioned by thinking about how we can deal with a quantum theory of gravitation. You can't represent gravity by a simple renormalisable theory like the Standard Model, so what do you do? In fact, you treat general relativity the same way you treat low-energy pions, which are described by a low-energy non-renormalisable theory. (You could say it's a low-energy limit of QCD but its ingredients are totally different – instead of quarks and gluons you have pions). I showed how you can generate a power series for any given scattering amplitude in powers of energy rather than some small coupling constant. The whole idea of EFT is that any possible interaction is there: if it's not forbidden it's compulsory. But the higher, more complicated terms are suppressed by negative powers of some very large mass because the dimensionality of the coupling constants is such that they have negative powers of mass, like the gravitational constant. That's why they're so weak.

If you recognise that the Standard Model is probably a low-energy limit of some more general theory, then you can consider terms that make the theory non-renormalisable and generate corrections to it. In particular, the Standard Model has this beautiful feature that in its simplest renormalisable version there are symmetries that are automatic: at least
to all orders of perturbation theory, it can’t violate the conservation of baryon or lepton number. But if the Standard Model just generates the first term in a power series in energy and you allow for more complicated non-renormalisable terms in the Lagrangian, then you find it’s very natural that there would be baryon and lepton non-conservation. In fact, the leading term of this sort is a term that violates lepton number and gives neutrinos the masses we observe. I wish I could claim that I had predicted the neutrino mass, but there already was evidence from the solar neutrino deficit and also it’s not certain that this is the explanation of neutrino masses. We could have Dirac neutrinos in which you have left and right neutrinos and antineutrinos coupling to the Higgs, and in that way get masses without any violation of lepton-number conservation. But I find that thoroughly repulsive because there’s no reason in that case why the neutrino masses should be so small, whereas in the EFT case we have Majorana neutrinos whose small masses are much more natural.

On this point, one doesn’t see the small value of the cosmological constant and Higgs mass undermine the EFT view by pointing to some fine-tuning? Yes, they are a worrying about things we don’t understand. The Higgs mass is very low, after all it’s only about a hundred times larger than the proton mass and we know why the proton mass is so small compared to the GUT or Planck scale; it is because the proton gets its mass not from the Higgs fields, which have to do with the Higgs, but from the QCD forces, and we know that these become strong very slowly as you come down from high energy. We don’t understand this for the Higgs mass, which, after all, is a term in the Lagrangian, not like the proton mass. But it may be similar – that’s the old technicolour idea, that there is another coupling alongside QCD that becomes strong at some energy where it leads to a potential for the Higgs field, which then breaks electroweak symmetry. Now, I don’t have such a theory, and if I didn’t I wouldn’t know how to test it. But there’s at least a hope for that. Whereas regards to the cosmological constant, I can’t think of anything along that line that would explain it. I think it was Nima Arkani-Hamed who said something like the anthropic principle works for the cosmological constant, maybe that’s the answer with the Higgs mass – maybe it’s got to be small for anthropic reasons.” That’s very disturbing if it’s true, as we’re going to be left waving our hands. But I don’t know.

Early last year you posted a preprint “Models of lepton and quark masses” in which you returned to the problem of the fermion mass hierarchy. How was it received?

Even in the abstract I advertise how this isn’t a realistic theory. It’s a problem that I first worked on almost 50 years ago. Just looking at the table of elementary particle masses I thought that the electron and the muon were crying out for an explanation. The electron mass looks like a radiative correction to the muon mass, so I spent the summer of 1973 on the back deck of our house in Cambridge, where I said, “This summer I am going to solve the problem of calculating the electron mass as an order-\(10^{-13}\) correction to the muon mass.” I was able to prove that if in a theory it was natural in the technical sense that the electron would be massless in the tree approximation as a result of an accidental symmetry, then at higher

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fermion, the muon. Is there reason to think the Higgs might not couple to all three generations? Before the Higgs was discovered it seemed quite possible that the explanation of the hierarchy problem was that there was some new technicolour force that gradually became strong as you came from very high energy to lower energy, and that somewhere in the multi-TeV range it became strong enough to produce a breakdown of the electroweak symmetry. This was pushed by Lenny Susskind and myself, independently. The problem with that theory was: how did the quarks and leptons get their masses? Because while it gave a very natural and attractive picture of how the W and Z get their masses, it left it really mysterious for the quarks and leptons. It’s still possible that something like technicolour is true. Then the Higgs coupling to the quarks and leptons gives them masses just as expected. But in the old days, when we took technicolour seriously as the mechanism for breaking electroweak symmetry, which, since the discovery of the Higgs we don’t take seriously anymore, even then there was the question of how, without a scalar field, can you give masses to the quarks and leptons. So, I would say today, it would be amazing if the quarks and leptons were not getting their masses from the expectation value of the Higgs field. It’s important now to see a very high precision test of all this, however, because small effects coming from new physics might show up as corrections. But these days any suggestion for future physics facilities gets involved in international politics, which I don’t include in my area of expertise.

Any more papers or books in the pipeline? I have a book that’s in press at Cambridge University Press called Foundations of Modern Physics. It’s intended to be an advanced undergraduate textbook that takes you from the earliest work on atoms, through thermodynamics, transport theory, Brownian motion, to early quantum mechanics, and I even have two chapters that probably go beyond what any undergraduate would want, on nuclear physics and quantum field theory. It unfortunately doesn’t fit into what would normally be the plan for an undergraduate course, so I don’t know if it will be widely adopted as a textbook. It was the result of a lecture course I was asked to give called “thermodynamics and quantum physics” that has been taught at Austin for years. So, I said “alright”, and it gave me a chance to learn some thermodynamics and transport theory.

Interview by Matthew Chalmers.
The hitchhiker’s guide to weak decays

Gauge Theory of Weak Decays: The Standard Model and the Expedition to New Physics Summits
By Andrzej J Buras
Cambridge University Press

Don’t forget your towel! Andrzej Buras’s new book is an indispensable travel guide to unexplored territory in weak decays, writes our reviewer.

As Buras describes with clarity, signals of new physics in the weak decays of K, B, and B mesons, and other rare low-energy processes, can manifest themselves as deviations from the precise predictions of the corresponding decay rates that are able to derive within the SM. In the absence of a reference beyond-the-SM theory, it is not clear where, and at which level of precision, these deviations could show up. General quantum field theory arguments suggest that weak decays are particularly sensitive probes of new physics, as they can often be predicted with high accuracy within the SM.

The two necessary ingredients for a journey in the realm of weak decays are therefore precise SM predictions on the one hand, and a broad—spectrum investigations of beyond-the-SM sensitivity on the other. These are precisely the two ingredients of Buras’s book. The first part, he guides the reader through all the steps necessary to arrive to the most up-to-date predictions for rare decays. This part of the book offers different paths to different readers: students are guided, in a very pedagogical way, from tree-level calculations to high-precision multi-loop calculations. Experienced readers can directly find up-to-date phenomenological expressions that summarise the present knowledge on virtually any process of current experimental interest. This part of the book can also be viewed as a well-thought-out summary of the history of precise SM calculations for weak decays, written by one of its most relevant protagonists.

The second part of the book is devoted to physics beyond-the-SM. Here the style is quite different: less pedagogical and more encyclopaedic. Employing a pragmatic approach, which is well motivated to discuss low-energy processes, extensions of the SM are classified according to properties of hypothetical new heavy particles, from Z’ bosons to leptoquarks, and from charged Higgs bosons to “vector-like” fermions. This allows Buras to analyse the impact of such models on rare processes in a systematic way, with great attention paid to correlations between observables.

To my knowledge, this book is the first comprehensive monograph of this type, covering far more than just the general aspects of SM physics, as may be found in many other texts on quantum field theory. The uniqueness of this book lies in its precise details on a wide variety of interesting rare processes. It is a key reference that was previously missing, and promises to be extremely useful in the coming decades.

Gino Isidori
University of Zurich.

The Science of Learning Physics: Cognitive Strategies for Improving Instruction
By José P Mestre and Jennifer Docktor
World scientific

A means for lecturers to reflect on and enrich their teaching strategies

Transfixed in admiration. This is not the teaching style advocated by José Mestre and Jennifer Docktor in their new book. The Science of Learning Physics. And it’s no longer typical, say the authors, who suggest that approximately half of physics lecturers use at least one
interactive mid-lecture quiz. At you – albeit so the students can snap having a hundred camera phones pointed at you - almost so the students can snap a QR code on your slides to take part in an interactive mid-lecture quiz.

“evidence-based instructional practice” - jargon, most often, for an interactive teaching method. As colleagues joked when I questioned them on their teaching styles, there is still a performative aspect to lecturing, but these days it is just as likely to reflect the rock-star feeling of having abonded camera phones pointed at you - almost so the students can snap a QR code on your slides to take part in an interactive mid-lecture quiz.

Mestre and Docktor, who are both educational psychologists with a background in physics, offer intriguing tips to maximise the impact of such practices. After answering a snap poll, they say, students should discuss with their neighbour before being polled again. The goal is just to allow the lecturer to tailor their teaching, but also to allow students to “construct” their knowledge. Lecturing, they say, gives piecemeal information, but does not connect it. Neurons fire, but synaptic connections are not trained. And as the list of neurotransmitters that influence synaptic connections includes dopamine and serotonin, making students feel good by answering questions correctly may be worth the time investment.

Relative to other sciences, physics lecturers are leading the way in implementing evidence-based instructional practices, but far too few are well trained, say Mestre and Docktor, who want to bring the tools and educational philosophies of the high-school physics teacher to the lecture theatre. Swiss and Soviet developmental psychologists Jean Piaget and Lev Vygotsky are duty named, though. “Think-pair-share”, miss whiteboards and flipping the classroom (not a disresolute gesture but the advance viewing of pre-recorded lectures before a more participatory lecture), are the order of the day. Students are not blank slates, they write, but have strong attachments to deeply ingrained and often erroneous intuitions that they have previously constructed. Misconceptions cannot be supplanted wholesale, but must be unknotted strand by strand. Lecturers should therefore explicitly describe their thought processes and encourage students to reflect on “metacognition”, or “thinking about thinking”. Here the text is reminiscent of Nobelist Daniel Kahneman’s seminal text Thinking, Fast and Slow, which divides thinking into two types: “system 1”, which is instinctive and emotional, and “system 2”, which is logical but effortful. Lecturers must fight against “knee-jerk” reasoning, say Mestre and Docktor, by modelling the time-intensive construction of knowledge, rather than aspiring to misleading virtuosic displays of mathematical prowess. Whenever possible, this should be directly assessed by giving marks not just for correct answers, but also for identifying the “big idea” and showing your working.

Disappointingly, examples are limited to pulleys and ramps, and, somewhat ironically, the book’s dusty academic tone may prove ineffective at teaching teachers to teach. But no other book comes close to The Science of Learning Physics as a means for lecturers to reflect on and enrich their teaching strategies, and it is highly recommended on that basis. That said, my respect for my old general-relativity lecturer remained undimmed as I finished the last page. Those old-fashioned lectures were hugely inspiring - a “non-cognitive aspect” that Mestre and Docktor admit their book does not consider.

Mark Rayner, associate editor.
Gain unique insights on the latest research breakthroughs and project developments in particle physics and related fields
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CERN employs around 2600 staff members who design, build, operate, maintain and support an infrastructure used by a much larger worldwide community of physicists. Of these, only 19% are research physicists. The core hiring needs are for engineers, technicians and support staff in a wide variety of domains: mechanical, electrical, engineering, vacuum, cryogenics, civil engineering, radiation protection, radio-frequency, computing, software, hardware, data acquisition, materials science, health and safety… the list goes on. Furthermore, there are also competences needed in human resources, legal matters, communications, knowledge transfer, finance, firefighters, medical professionals and other support functions.

On the radar

The challenge is to put CERN “on the radar” of people who would not normally identify it as a possibility to pursue their career. There is a need to attract candidates from across all CERN’s 32 Member and Associate Member States. In what is already a competitive market, attracting people from a large multitude of disciplines to an organisation whose reputation revolves around particle physics can be a challenge. So how is this challenge tackled? CERN has established a well-established “employer brand”, targeting of, for example, a mechanical technician in all CERN Member States, creative and innovative approaches have to be utilised. The varying landscapes, cultural preferences and languages come into play, and this is compounded by the different job-seeking behaviours of students, graduates and experienced professionals through a constantly evolving ecosystem of channels and solutions. A widespread presence is key. The cornerstones are: an attractive careers website; professional networks such as LinkedIn to promote CERN’s employment opportunities; and practically attracting candidates; social media to increase visibility of hiring campaigns; and being present on various job portals, for example in the oil, gas and energy arenas. Outreach events, presence at university career fairs and online webinars further serve to present CERN and its diverse opportunities to the targeted audiences.

Storytelling is an essential ingredient in promoting our opportunities, as are the experiences of those already working at CERN. In the words of Håvard, an electromechanical technician from Norway: “I got to challenge myself in areas and with technology you don’t see any other place in the world.” Gunnar, a firefighter from Germany describes, “I am working as a

I get to challenge myself in areas and with technology you don’t see any other place in the world

While CERN holds a natural attraction for physicists, hiring the engineers, technicians and others who build, operate and maintain the lab’s complex infrastructure is more challenging, explains Anna Cook.

CERN enjoys a world-class reputation as a scientific laboratory, with the start-up of the Large Hadron Collider and the discovery of the Higgs boson propelling the organisation into the public spotlight. Less tangible and understood by the public, however, is that to achieve this level of success in cutting-edge research, you need the infrastructure and tools to perform it. CERN is an incredible hub for engineering and technology – hosting a vast complex of accelerators, detectors, experiments and computing infrastructure. Thus, CERN needs to attract candidates from across a wide spectrum of engineering and technical disciplines to fulfil its objectives.

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Appointments and awards

ESA announces new DG
The European Space Agency (ESA) Council has appointed Josef Aschbacher as its new director general for a period of four years. He will succeed Jan Wörner from 30 June. Aschbacher is currently ESA director of Earth observation programmes and head of ESA’s centre for Earth observation near Rome. Born in Austria, he studied at the University of Innsbruck, where he obtained Masters and PhD degrees in natural sciences. He has more than three decades of experience working in international organisations, including ESA, the European Commission, the Austrian Space Agency and the Asian Institute of Technology.

JINR director change
Grigory Trubnikov has been appointed as the new director of the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. Trubnikov, who first joined JINR in 1996 as a researcher, was previously vice-director at JINR and served as Russia’s deputy minister of education and science from 2017-2020. He replaces Victor Maruyev, who was JINR director since 2012. With a term time of five years, Trubnikov will oversee an important period at JINR, with the scheduled completion of the NICA complex in 2022 (see p9).

SCIPP's new skipper
Jason Nielsen of the University of California at Santa Cruz has taken over as director of the Santa Cruz Institute for Particle Physics (SCIPP), succeeding Steven Ritz who steps down after 10 years at the helm. Nielsen, who has served as associate director of SCIPP for the past eight years, started out on the ALEPH experiment at LEP and is a long-standing member of the ATLAS collaboration, for which he currently serves on the management advisory committee for the US ATLAS organisation.

France. Godbole was recognised for her contributions towards collaborations between France and India and for her role in promoting women’s visibility in science. Godbole’s decades of work in particle physics has ranged from supersymmetry to electroweak theory, and she is currently a member of the international detector advisory group for the International Linear Collider.

IceCube awarded Rossi Prize
The 2021 Bruno Rossi Prize was awarded to Francis Halzen (below) and the IceCube Collaboration for the discovery of a high-energy neutrino flux of astrophysical origin. Halzen is principal investigator and co-spokesperson of the IceCube project based at the South Pole, which in September 2017 detected a high-energy neutrino from the direction of a blazar, providing the first evidence of a source of high-energy cosmic rays. The Bruno Rossi Prize is awarded for a significant contribution to high-energy astrophysics, with a particular emphasis on source work.

2020 Pomeranchuk Prize
Theorists Sergio Ferrara (CERN) and Mikhail Vasiliev (Lebedev Institute) were awarded the 2020 Pomeranchuk Prize, which has been granted annually since 1998 by the Institute for Theoretical and Experimental Physics in Moscow. Ferrara (top), who co-discovered supergravity in 1976 along with Daniel Freedman and Peter van Nieuwenhuizen, was cited “for his contribution to fundamental aspects of supergravity that has been a very important achievement for our understanding of modern supergravity theories”, while Vasiliev was recognised for an “outstanding series of papers” on the higher spin theory in Anti-de Sitter and de Sitter spaces.

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We participate in leading roles in particle physics projects on our campus and in international collaborations such as CERN or KEK. We develop technologies for detectors and accelerators, and work on scientific computing. We operate important infrastructure such as the Tau-2 centre or the electron test beam.

The position

You are invited to take an active role in one or more of the following projects in Hamburg:

- The ATLAS and CMS experiments at CERN or the Belle II experiment at KEK
- Experimental activities on-site (ALPS II and future on-site experiments)
- Preparations for future particle physics experiments, in particular detector and technology development
- Scientific computing
- Accelerator development

Requirements

- Ph.D. in physics (to be eligible, you have to take up the position at the earliest 5 years after your doctorate)
- Interest in particle physics
- Experience relevant in at least one of the areas listed above

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For our location in Zeuthen we are seeking:

Postdoc for the Photo Injector Test Facility PITZ in Zeuthen

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DESY, with its 2700 employees at its two locations in Hamburg and Zeuthen, is one of the world’s leading research centres. Its research focuses on decoding the structure and function of matter, from the smallest particles of the universe to the building blocks of life. In this way, DESY contributes to solving the major questions and urgent challenges facing science, society and industry. With its ultramodern research infrastructure, its interdisciplinary research platforms and its international networks, DESY offers a highly attractive working environment in the fields of science, technology and administration as well as for the education of highly qualified young scientists.

The Photo Injector Test Facility (PITZ) in Zeuthen near Berl is one of the leading international groups in developments on modern photo injectors and their applications. Current R&D goals of PITZ include improving electron source brightness beyond state of the art and demonstration of accelerator-based THz pump sources for high repetition rate X-ray Free-Electron Lasers (FEL) like FLASH and European XFEL. Such efforts require reliable and comprehensive electron beam characterization, i.e. a detailed reconstruction for both projected and time-resolved phase space measurements. The focus of the offered position will be on further developments of tools for the characterization of high brightness electron beams and start-to-end beam dynamics simulations for a commissioned new THz SASE FEL beamline.

The position

- Develop, test and support software packages for low-emittance electron beam characterization and THz SASE FEL commissioning
- Perform accurate modeling of experimental procedures for electron beam measurements including classification and analysis of systematic errors
- Carry out start-to-end simulations of the beam dynamics in the photo injector for operation conditions as well as for future applications
- Analyze experimental data and compare with start-to-end simulation results
- Participate in shift operation for accelerator R&D at PITZ and/or European research platforms and/or organisations

Requirements

- University degree in accelerator physics with PhD, with very good knowledge in accelerator physics and accelerator technology or equivalent qualification
- Relevant background in beam dynamics simulations of space charge dominated beams as well as in numerical and statistical methods
- Good knowledge and experience in characterization of particle beams using image processing, good programming skills and knowledge of high-level programming languages (Python/Matlab)
- Very good command of English is required and knowledge of German is of advantage
- Excellent teamwork abilities in an international environment
- For further information please contact Dr. Maks Spence at: spence@desy.de

The appointment is for a period of maximum five years. Reappointment is possible. The position is compensated at an international level in accordance with the W3 salary system in Germany which includes the option of performance-related payments.

DESY offers flexible work schemes, DESY’s goal is to promote more women into leadership positions. Applications from women will therefore be welcomed.

DESY offers a highly attractive working environment in the fields of science, technology and administration as well as the education of highly qualified young scientists.

Please note that it is the applicant’s responsibility that all material, including the references can be found here:

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A giant of the field

Jack Steinberger, a giant of the field who witnessed and shaped the evolution of particle physics from its beginnings to the confirmation of the Standard Model, passed away on 12 December aged 99. Born in the Bavarian town of Bad Kissingen in 1921, his father was a cantor and religious teacher to the small Jewish community, and his mother gave English and French lessons to supplement the family income. In 1934, after new Nazi laws had excluded Jewish children from higher education, Jack's parents applied for him and his brother to take part in a charitable scheme that saw 300 German refugee children transferred to the US. Jack found his home as a foster child, and was reunited with his parents and younger brother in 1938.

In 1935 Steinberger went to the Radiation Lab at the University of California at Berkeley, where he performed an experiment at the electron synchrotron that demonstrated the production of neutral pions and their decay to photon pairs. He stood only one year in Berkeley, partly because he declined to sign the anti-communist loyalty oath, and moved on to Columbia University. In 1948, Fermi, who was probably Jack's most influential physics teacher, described him as “direct, confident, without complication, he concentrated on physics, and that was enough.”

In 1949 Steinberger went to the Radiation Lab at the University of Chicago until 1942, when he joined the army and was sent to the MIT radiation laboratory to work on radar bomb sights. He was assigned to the antenna group where his attention was brought to physics. After the war he returned to Chicago to embark on a career in theoretical physics. Under the guidance of Enrico Fermi, however, he switched to the experimental side of the field, conducting mountain-top investigations into cosmic rays. He was awarded a PhD in 1949.

In the 1960s, the construction of a high-energy, high-flux proton accelerator at Brookhaven opened the door to the study of weak interactions using neutrino-beam experiments. This marked the beginning of Jack’s interest in neutrino physics. Along with Mel Schwarz and Leon Lederman, he designed and built the experiment that established the difference between neutrinos associated with muons and those associated with electrons, for which they received the 1988 Nobel Prize in Physics. Jack joined CERN in 1968, working on experiments at the Proton Synchrotron exploring CP violation in neutral kaons. In the 1970s, with the advent of new neutrino beams at the Super Proton Synchrotron, Jack became a founding member of the CERN–Dortmund–Heidelberg–Saclay (CDHS) collaboration. Running from 1976 to 1984, CDHS produced a string of important results using neutrino beams to probe the structure of the nucleon and the Standard Model in general. In particular, the collaboration confirmed the predicted variation of the structure function of the valence quarks with Q2 (nicknamed “scaling violations”), a milestone in the establishment of QCD.

When the Large Electron–Positron (LEP) collider was first proposed, a core group from CDHS joined physicists from other institutions to develop a detector for CERN’s new flagship collider. This initiative grew into the ALEPH experiment, and Jack, a curious and imaginative physicist with an extraordinary rigour, was the natural choice to become its first spokesperson in 1980, a position he held until 1990. From the outset, he stipulated that standard solutions should be adopted across the whole detector as far as possible. This led to the end-caps reflecting the design of the central detector, for example. Jack was also insistant that all technologies considered for the detector first had to be completely understood. As the LEP era got underway, this level of discipline was reflected in ALEPH’s results.

Next to physics, music formed an important part of Jack’s life. He organised gatherings of amateurs, and occasionally professional, musicians at his house. These were usually marathons of Bach, starting in the late afternoon and continuing until the late evening. In his autobiography, Jack summarised: “Play the flute, unfortunately not very well, and have enjoyed tennis, mountaineering and sailing, passionately.”

Jack retired from CERN in 1986 and went on to become a professor at the Scuola Normale Superiore di Pisa. President Ronald Reagan awarded him the National Medal of Science in 1988. In 2001, on the occasion of his 80th birthday, the city of Bad Kissingen named its gymnasium in his honour. Jack continued his association with CERN throughout his 90s. He leaves his mark not just on particle physics but on all of us who had the opportunity to collaborate with him.

His friends and colleagues.

A curious and imaginative physicist with an extraordinary rigour

Jack photographed at CERN in 2016.
Veltman made a lasting impact on particle physics, and inspired many students

André Martin 1929–2020

An ambassador for CERN

André Martin passed away on 11 November 2020, marking a great loss to the theory community worldwide and to the CERN family. André was born in Paris on 20 September 1929 and studied physics at the École Normale Supérieure (ENS) and the University of Paris. His thesis adviser was Maurice Lévy (ENS theory group), with whom he has subsequently worked on common projects. André arrived at CERN in 1959 as a fellow, became a staff member in 1964, and an honorary member in 2019, working up until a few days before he was admitted to hospital, diagnosed with coronavirus and died of pneumonia. He led a cosmopolitan life, travelling all over the world, and had friends and colleagues all over. He had long and productive visits to various US institutions, including Princeton, Stony Brook, Seattle, Caltech, Los Alamos and Rockefeller. André was proud to have contributed to the launching of the Cargese school and supervised 26 PhDs. He was a member of the Royal Swedish Academy of Sciences, the Académie des Sciences, and the American Physical Society. He was awarded the V. Weisskopf prize in 1999 and the Tannoudji prize in 2017.

Günther Plass 1930–2020

Decisive contributions to CERN

Günther Plass, a former CERN director of accelerators, passed away in his home town of Barmen, Germany, in 2020. Günther joined CERN in 1956, participating in the construction of the Proton Synchrotron (PS) as a member of the magnet group. Over the years, he made major contributions to the concept and development of the PS complex, the heart of CERN’s accelerator chain. This was also his area of expertise: Günther was the right person for a task or project. He was an ambassador in the truest sense of the word, with an intense cultural and social life. His hospitality was extraordinary, and it was a pleasure to enjoy their immense culture in literature and art. They are survived by their two sons, Roland and Sandro, and two grandchildren, Raul and Joanne. André had friends in almost every university in the world, and more to come. Some of his best ambassadors and advocates. He will be sorely missed.
An all-round experimentalist

Stephen Reucroft 1943–2020

Experimental particle physicist Stephen Reucroft passed away in October 2020 after a long struggle against cancer. He grew up in Yorkshire, UK, earning a PhD in particle physics in 1969 from the University of Liverpool. His early research career focused on precision measurements using the high-resolution rapid-cycling bubble chambers HYFCC and LEBE at the CERN PS and SPS. These included resonance properties, hyperon magnetic moments, and charm-particle production and decay. He was the CERN-EP group leader for the North Area experiments NA13, 16 and 27. Subsequently, he was spokesperson of EN13, which took LEBE to Fermilab to successfully resolve a controversy about the energy dependence of the charm-production cross-section.

Steve became professor of physics at Northeastern University, Boston, in 1986, working at the high-energy particle facilities there: the medium-energy electron synchrotron, the heavy ion synchrotron, and the 36-inch superconducting solenoid. From 1999, he held a joint appointment at Northeastern and Tufts University. He served as spokesperson of the L3 experiment and proposed for the SSC, and built up and led a large research group on the L1 and DO experiments working on precision electroweak and QCD measurements, among many others. An early collaborator on the CMS experiment, Steve led a consortium of eight NSF-supported university groups that made major contributions to the electromagnetic calorimeter (especially the novel avalanche photodiode sensors), software and computing systems, and physics analyses. He actively promoted technology transfer from academia to industry and co-founded a non-profit company in Boston that was the first to bring silicon photomultipliers to market. He also initiated a cloud service for the protection of elderly and fragile people, and launched a crowd-funding campaign to advance next-generation nuclear energy technologies.

Steve was a strong advocate for young scientists, advising more than 45 PhD students and postgraduates, and was very active in scientific outreach. He co-founded the Research Experience for Undergraduates (REU) programme at CERN, judged the Intel (now Regeneron) International Science and Engineering Fair, and co-wrote a science column for The Boston Globe newspaper. He wrote numerous academic papers, popular articles and books, was a regular contributor to CERN Courier, and was elected to the National Association of Science Writers.

Steve was invariably cheerful with a unique sense of humour, and his door was always open. He will be much missed.

Lucas Taylor

An expert engineer

Jean-Claude Berset 1935–2020

CERN engineer Jean-Claude Berset passed away on 3 October at the age of 84. Jean-Claude arrived at CERN in 1970 and was assigned as an electronics technician in the former ND division, developing front-end electronics. He participated in the development and construction of systems for various experiments at CERN, from his early days on the PS and ISR, then SPS, LEP and finally the LHC, where he worked on the development of the readout electronics for the ALICE time projection chamber—a system that was in operation until very recently. Jean-Claude retired from CERN in 2005. His colleagues remember him not only as an expert and competent engineer, highly skilled, analytical, meticulous and always ready to help, but also a colleague and friend, who understood and fathomed human qualities we will treasure.

His colleagues and friends in the ALICE collaboration.

Jean-Claude worked on the PS and ISR, SPS, LEP and finally the LHC.
Notes and observations from the high-energy physics community

The great physics bake-off

Cakes were baked, votes were counted, and UK student Maddie Watkins beat off stiff competition from a baker’s dozen of high-energy physicists to be crowned star baker of the inaugural Great PhysicsBakeoff for her depiction of Accidental wormhole vuurka moment. “We had gravitational-lensing gateaux, stellar-mass synthesis sponge and recreations of the International Space Station, the NASA Space Shuttle and Fermilab’s iconic Wilson Hall,” says organiser Katherine Leney (Southern Methodist University) of the January competition, which took place on social media. “We’re still wondering if you love eating antiparticle cupcakes,” adds co-organiser Shep Hills (STFC).

ATOMKI boson under fire

Particle physicists in Canada and the US have added a new twist to the tale of the ATOMKI anomaly – a reported 6.8 σ excess of electron-positron pairs created during nuclear transitions of excited “nuclear haloes” (270) has been proposed as an explanation (CERN Courier January/February 2019 p37). In a preprint posted on 3 February, Aleksandra Aleksejevs (Memorial University of Newfoundland) and co-workers pour cold water on this interpretation, arguing that the anomaly can be explained by adding the full set of second-order corrections and the interference terms to the Born-level decay anomaly can be explained by adding the full set of second-order corrections and the interference terms to the Born-level decay anomaly.

From the archive: April 1981

Antiprotons à gogo

0113–14 February 1981 was a special time for the world’s first antiproton synchrotron. Intense pulses of 5.6 GeV antiprotons from the Antiproton Accumulator are accelerated to 26 GeV in the PS for use in proton–antiproton collisions in the Intersecting Storage Rings or in the Super Proton Synchrotron, SPS, after subsequent acceleration (achieved on 1 July at 540 GeV centre-of-mass energy) in the search for the elusive intermediate bosons of weak interactions. At the other end of the energy scale, preparations are under way in the PS South Hall to construct a Low Energy Antiproton Ring, LEAR, providing intense antiproton beams in the energy range 0.1 to 2 MeV. Investigations of proton–antiproton annihilation should improve our knowledge of quark behaviour. LEAR physics will also cover protonium spectroscopy, exotic proton–antiproton annihilation, and provide a definitive answer on baryonium, states formed from baryons and antibaryons.

#GreatPhysicsBakeOff for her

The Financial Times(27 January) about the new supercollider!

“Today, Jane Street’s source code is 25Miles long, about as much as the Large Hadron Collider uses.”

The Financial Times (28 January) channels CERN to communicate the complexity of the algorithms used by quantitative trading firm Jane Street.

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